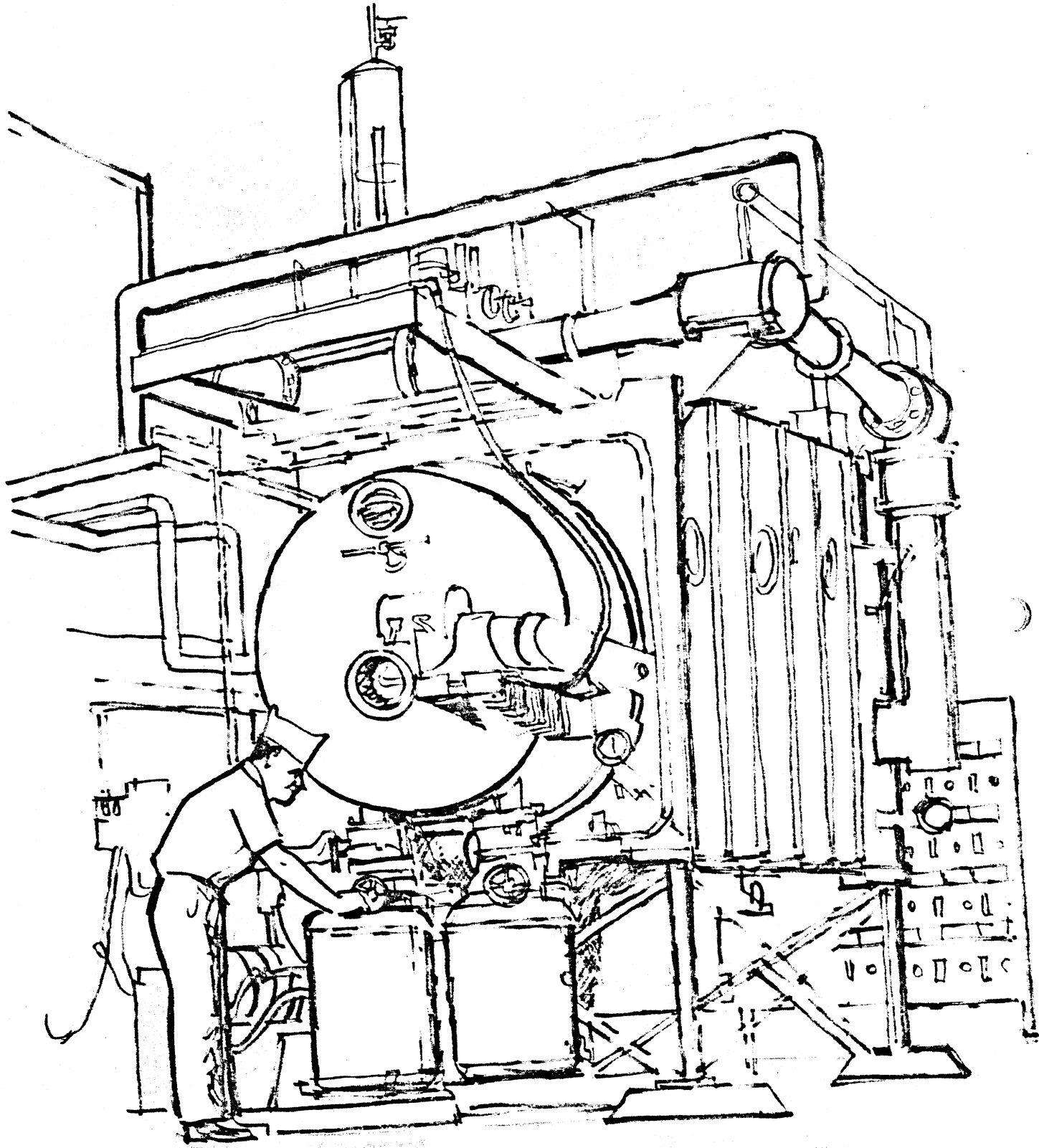


# VACUUM FOAM-DRIED WHOLE MILK

A Success Story in Cooperative Research Effort

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EVER since the early 13th century, efforts have been made to facilitate the storage and transport of milk by removing its water content. Marco Polo reported that a form of dry whole milk was used by the soldiers of Genghis Khan as part of their rations (13).<sup>1</sup> Although numerous attempts have been made since that era to produce a satisfactory dry whole milk, documentation of the methodology used did not appear in the literature until the 19th century. According to the technical and patent literature, technicians and chemists were trying to devise suitable methods for making a good dry whole milk throughout most of that century. The degree of success of these ventures can be inferred from the comment of Fleischmann, a noted German dairy scientist, who indicated in 1901 that it would not be possible to produce a marketable dry whole milk worthy of the name (13).

Despite Fleischmann's discouraging pronouncement, work has continued on the problem to this day. Two factors have served as strong incentives to

carry on further research: The desirability of lengthening the storage life of milk, and the seemingly wasteful occupation of carting around the country enormous volumes of liquid that contains more than 80 percent water.

During the 1950's, research on the problem intensified considerably—chiefly because of the impetus received from the development of successful methods for making dry skim milk. It appeared that these newer technologies might be adaptable for making an acceptable dry whole milk product. The assignment to tackle the problem in earnest was given to chemical engineers at the Philadelphia laboratory of the Department of Agriculture's Eastern Utilization Research and Development Division in 1955. What followed was more than a decade of painstaking research effort alternately marked by temporary setbacks and rewarding breakthroughs that ultimately led to an economically feasible process for making a dry whole milk of good quality. This article tells the story of that research effort—in somewhat abbreviated form, of course, because of space limitations and an attempt to maintain some degree of continuity.

<sup>1</sup> Italic numbers in parentheses refer to Literature Cited, p. 41.

## The Background

AS mentioned above, previously developed methods for making a marketable dry skim milk provided a good starting point for modern research on making a satisfactory dry whole milk. Two methods are currently used in manufacturing the skim product—spray drying and roller drying. Of the two, spray drying is the more important (4) because it provides, through certain modifications, the means for obtaining “instant” dispersibility—that is, the ability to dissolve quickly in water with a minimum of stirring. These modifications of the spray-drying method were developed since World War II, and because of further refinements of the process, dry skim milk has become a successful product of commerce.

Instantizing techniques, however, have not been suited to dry whole milk (14). From a flavor standpoint, too, major problems arise when drying whole milk that are absent in the case of skim. Dry whole milk made by earlier methods has been described as (a) very difficult to disperse (particularly without using warm water), (b) inclined to taste highly cooked and “eggy,” and (c) deteriorating during storage to flavors such as tallowy, rancid, stale, burnt feathers, etc. (15).

This was the state of the art when the present work was begun in the Department of Agriculture. The objective of our research was to develop a commercially feasible process for the preparation of a beverage-quality dry whole milk that would disperse easily in cold water, have the flavor of fresh whole milk when newly prepared, and maintain those properties for a reasonable time in storage (6 to 8 months at 40° F).

## Development of the Batch Process

BECAUSE of the poor quality of the dry whole milks available when this work began, the first problem seemed to be to determine if it would be *even possible* to produce a dry whole milk of the desired good flavor and easy dispersibility. In the usual drying practice, fresh flavor was lost by “forewarming” the milk—that is, subjecting it to high heat before the actual drying process. Forewarming was thought to be necessary because it either (a) produced natural antioxidants needed to combat fat oxidation during spray drying and storage, or (b) destroyed

the oxidizing enzymes present in milk (13). But because the treatment also imparted a cooked flavor to the milk, we decided to eliminate this step if possible.

Another obvious way to avoid oxidation during drying was to dry under vacuum. Vacuum drying also appeared to offer rapid dispersibility through “puff-drying,” a technique in which a highly expanded, sponge-like structure is created by water vapor bubbles as they form in a liquid concentrate during vacuum drying. Puff-drying had produced dry fruit juices that dissolve rapidly in water (20). For these reasons, puff-drying techniques were used in the first attempts to produce a satisfactory dry whole milk. These experiments were carried out in a vacuum shelf dryer.

Puffed structures can be developed by various devices, and for materials which are readily soluble the type of structure may not be of prime importance for rapid dispersibility. With whole milk, however, the structure markedly influenced the dispersibility rate of the dried product.

Two possible structures are illustrated in figure 1. The puffed form on the top was developed during

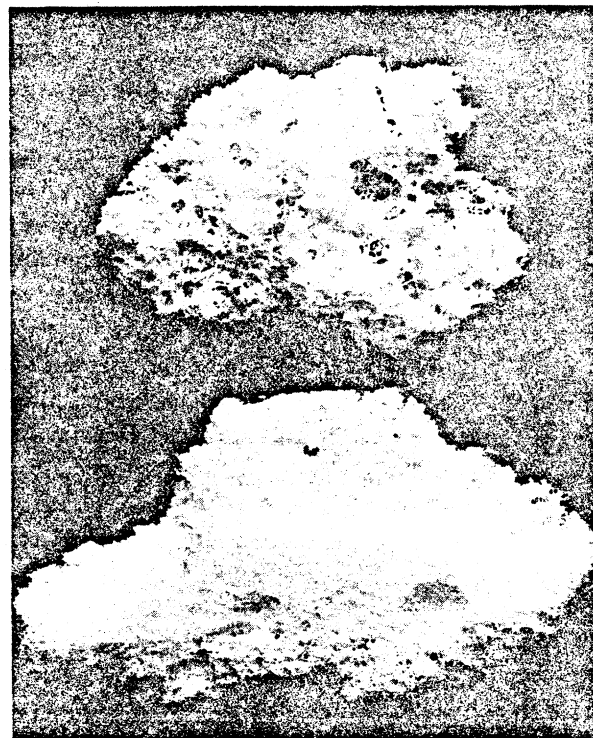


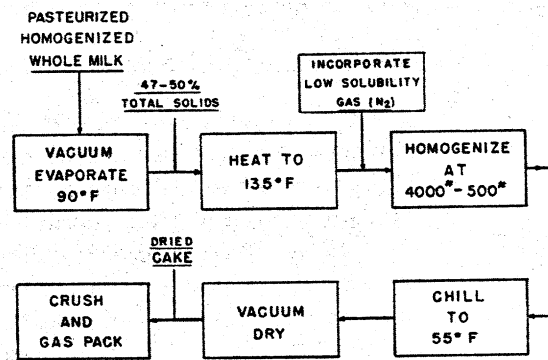
FIGURE 1.—Structures obtained by water vapor (top) and entrained gas of low solubility (bottom).

vacuum drying by boiling off the water vapor from a degassed concentrate—that is, one containing no trapped air or oxygen. The large, nonuniform bubbles had a heavy, tough, intercellular structure, and dispersed very poorly. The puffed product on the bottom was formed by the expansion of the low solubility trapped nitrogen gas in the concentrated milk as the pressure in the dryer was reduced. This form has small, uniform bubbles and a fine, fragile, intercellular structure. This new, desirable form was called “foam” (19).

Further experimentation showed that the mere use of an entrained (trapped-in) gas does not insure a form that will disperse readily. In order for entrained gas to be effective in forming a fine-grained foam as pressure is reduced, the concentrate must be held at a low enough temperature to allow the entrained gas to expand sufficiently *in situ* to form the foam before the pressure in the dryer reaches the flash point of the concentrate. If the flash point is reached first, the concentrate will boil, removing the entrained gas. The resulting structure will then be the form caused by bubbles of water vapor in a degassed concentrate (19).

Much of the research effort that went into the development of a satisfactory batch process was guided by scientific intuition—a characteristic of a research worker that quite often brings rewarding dividends. It should be pointed out here also that our chemical engineering research team was primarily skilled in the basic principles of drying heat-sensitive liquid materials; we knew much less about milk *per se*. In the daily laboratory procedure, which continued for nearly 4 months, various modifications had to be proved as being practical and feasible or else unrealistic for our purposes. After the 43d batch had been run, it appeared that the process had finally been perfected to the degree deemed necessary for moving to the next step.

In the flow diagram for the batch process as finally developed (fig. 2), fresh pasteurized, homogenized milk is concentrated to about 48 percent solids content at 90° F in a high vacuum, falling-film evaporator. It is then heated to 135° F and homogenized, first at 4000 psi and then at 500 psi, in a single-stage homogenizer of the pulsator type. Immediately prior to homogenization, nitrogen is bubbled through the concentrate, dispersing entrained gas through the material. The concentrated



PROCESS FOR AN IMPROVED DRIED WHOLE MILK

FIGURE 2.—Flow diagram for batch process.

milk is then flowed over stainless steel drying pans to an average depth of 1/16 inch, chilled to 55° F or below, and dried as a foam in a vacuum shelf drier. The resulting dried mass is crushed lightly through stainless steel screens.

In vacuum foam-drying, two separate phenomena occur sequentially under vacuum. In the first the foam is created, and in the second the foam is dried. In puff-drying, on the other hand, the puff is formed during and as a result of the drying proper.

#### Need for Testing

**ALTHOUGH** the product resulting from vacuum foam-drying appeared to be what we were looking for, it needed to be thoroughly tested for dispersibility and other factors. Screening the foam through 20-mesh resulted in more rapid dispersing but a more bulky product than screening through 40-mesh. Dispersibility of the product was unimpaired after a year's storage at 73° F, but deteriorated at 100° F. Forewarming resulted in a more rapid loss of dispersibility during storage at 100° F, and there was no apparent improvement in flavor stability (10).

Storage studies also showed that with oxygen present in the container at 73° F, the product stored best if the moisture content was between about 2.8 percent and 5.1 percent (2). Very important findings for the future work were that the 5-hydroxymethylfurfural content (an intermediate product in the browning process) of the freshly-dried product could be used both as a measure of the heat treatment undergone during processing, and as an in-

indicator of the future storage stability of the product (5). These findings were so important that research was carried out on the method of analysis (9).

#### *Development of the Continuous Process*

THROUGHOUT all phases of our research on developing a dry whole milk, we had to keep constantly in mind the objective of quality. The high standard arbitrarily set accounts in part for the months of effort devoted to measuring all aspects of the batch output. When the product aspect of the objective was satisfied by the development of the vacuum foam-drying process, the next problem was to determine whether the process was economically feasible on a commercial scale. An economic analysis by our cost engineers showed that the batch process was too costly to be of commercial significance, so an integrated pilot plant was designed and built for the translation of the batch process to a continuous one (1).

An apparent potential of continuous vacuum drying of whole milk not found in batch vacuum drying or conventional air drying was that it may be possible in a continuous vacuum operation to dry, handle, and package the milk with virtually no contact with oxygen once the milk enters the processing lines. If this could be accomplished, oxidation might be eliminated as the major off-flavor problem that had long plagued the dry milk industry. Thus, the continuous operation was designed to integrate all phases of the manufacturing process including packaging so that the milk would not be exposed to more than trace amounts of oxygen from the time it entered the pasteurizing line until the consumer opened the package containing the dry product. Later experimental evidence showed that the continuous process had successfully simulated an oxygen-free process, and that this in turn had eliminated oxidation as a major off-flavor problem (3).

In the continuous process, raw whole milk is adjusted to 26 percent fat content (milkfat basis), pasteurized and homogenized according to accepted practice, and then concentrated in a single-pass, agitated falling-film vacuum evaporator to a constant apparent viscosity. Milk is introduced at the top of the evaporating section, and flows down the inside wall of the evaporator body while steam for evaporation is maintained on the outside wall. The

four blades of a rotor turning inside the body and clearing the inside wall by 1/32 inch spread the milk into a thin, turbulent film across the whole inside wall of the evaporator, thus providing highly efficient conditions for evaporation. In a descent of only 23 inches, the milk is evaporated at a high rate from 12 percent to 45 percent solids content. Viscosity is the control variable because it is a prime factor contributing to the formation and stability of fluid foams, and because in milk concentrates, viscosity and solids content do not correlate well from one batch to another.

Next, the concentrate is homogenized in a two-stage, single-pass, variable rate homogenizer operating at 3000 and 500 psi. The function of the second homogenization is to eliminate "oiling off" of the reconstituted milk. This treatment also reduces substantially all of the fat particles to below 2 microns in diameter. The homogenizer also acts as a pump that maintains the concentrate flow rate for gas dispersion. Nitrogen is metered into the concentrate stream just ahead of two scraped surface heat exchangers that simultaneously chill the concentrate to about 35° F and disperse the nitrogen to a bubble size of less than 75 microns. The gas-containing concentrate is then delivered to the dryer through a metering pump.

The key piece of equipment in the pilot plant is the continuous vacuum dehydrator. The dryer consists of an endless solid stainless steel belt 12 inches wide which alternately passes over heating and cooling drums. Drums are 2 feet in diameter and are spaced 9 feet between centers. Either vacuum or pressure steam can be supplied to the heating drum, and coolant at various temperatures can be circulated through the cooling drum. Heat can be applied to either side of the belt between the two drums by means of banks of individually controlled electrical radiant heaters. The whole apparatus is enclosed in a chamber where pressures can be maintained from 50 to 0.5 mm Hg absolute.

The gas-containing concentrate is then metered to the dryer through a feed line which is jacketed by a cooling pipe. The feed temperature is adjusted to be below the flash point when it enters the drying chamber. Nitrogen in the concentrate expands in the nozzle and the resulting foam issues as a thin, uniform blanket or film. The belt carries the foam through the drying zones, where the moisture is

removed, to an oscillating doctor blade that removes the dry product from the belt. The product drops into a chute, then goes to a screw conveyor which carries it to one of two receivers.

### *Reducing the Cost*

THE work described above was a faithful translation of the batch process. An economic evaluation indicated that it, like the batch process, was too costly. The study further indicated that reduced costs could be obtained by reducing the bulkiness of the product as well as by increasing the dryer output, since packaging costs are lower for less bulky products. Thus, research was begun to seek changes in the continuous process in the interest of economy that would have little or no effect on product quality. The answer was found in a technique called "boil-down" (16). Just as in many other steps in our research and development process, the advice of cost engineers on the laboratory staff was the determining factor at this point as changes and improvement were considered, tried, and tested.

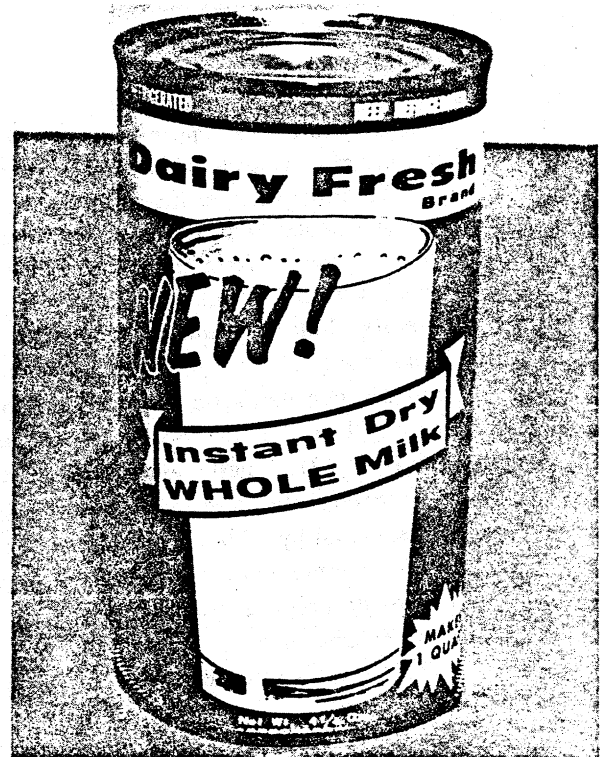
It is a generally valid proposition that thinner films provide higher rates of heat and mass transfer, so a reduction in foam thickness appeared desirable. We had learned, however, that at 3 mm Hg absolute dryer pressure, the thickness of the foam blanket reached a minimum at a nozzle opening of 0.047 inch (1) and that at smaller openings the foam blanket became thicker. Thus, foam thickness could not be reduced further by manipulating the nozzle. It would be necessary to somehow destabilize the foam structure once it had been applied to the belt. This was accomplished by raising the pressure in the drying chamber from 3.0 to 19.0 mm Hg absolute. At 19 mm, the foam structure partially broke down under the influence of heat ("boil-down"), leaving a thinner film. The increased chamber pressure that caused the foam to be only partly stable increased the output of the dryer by 43 percent and doubled the density, thus leading to lower production and packaging costs. This was gained, moreover, with a slightly improved quality due, no doubt, to the decreased drying time.

### *The Foam Stability Problem*

ALTHOUGH the "boil-down" technique improved the economic picture, we were then faced

with the problem of having no methodology for studying the properties of concentrated whole milk foams and characterizing their stability. Therefore, apparatus was developed for measuring two independent parameters—foaming ability and foam stability. Foaming ability is the initial height of a foam immediately after its formation in a column developed for the test; foam stability is the rate at which the foam subsides. We learned that the foaming ability of milk concentrates can only be described by a complex function of viscosity and temperature; that foaming ability reaches a minimum at about 70° F; and that the rate of foam subsidence can be described by an inverse exponential function of viscosity alone (11). The ratio of foaming ability to foam stability was a measure of foam behavior that could be used as a parameter in later mathematical studies of the process (6, 7).

In addition to the complex response of milk concentrate foams to viscosity and temperature, we observed that the behavior of concentrates was also affected by a seasonal influence (16). In winter the foams were relatively unstable, in summer they were relatively stable, and in spring and fall they



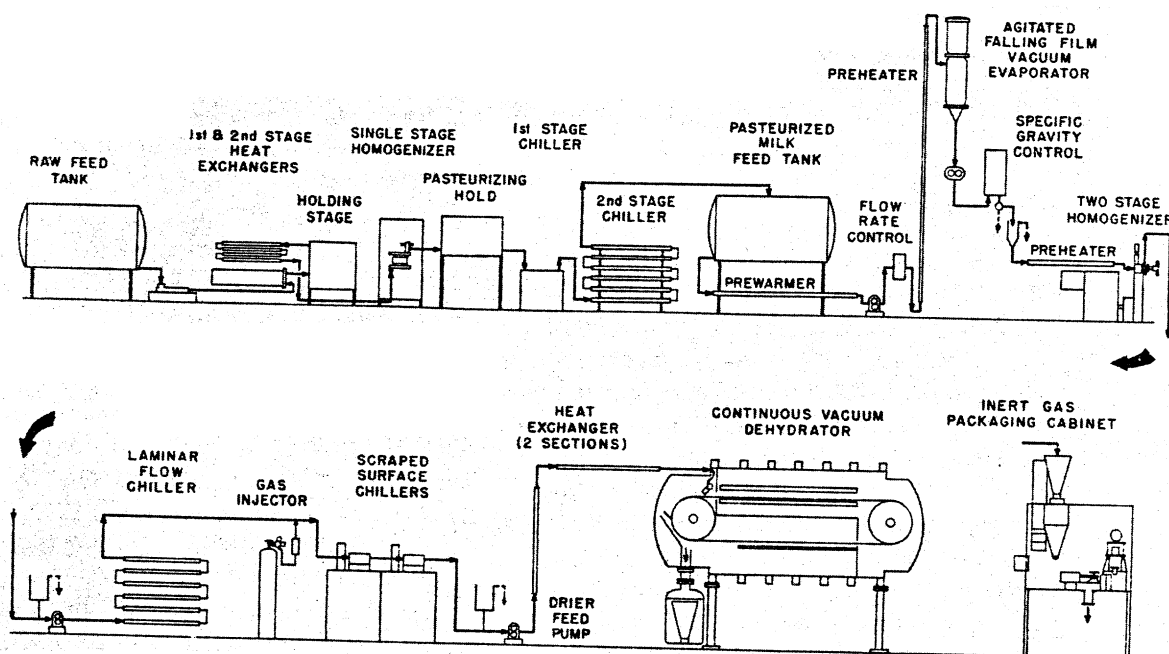


FIGURE 3.—Pilot plant for vacuum foam-dried whole milk.

passed through transitional periods of stability. Such behavior was undesirable, because the least extreme would cause the process to be non-reproducible on a year-round basis, and at the most it would even cause the process to be unworkable during part of the year. Research was therefore necessary to either determine the cause and cure of this effect or to show how to compensate for it.

After three years of intensive research effort, our results showed that the concentrations of all the whey protein fractions except  $\beta$ -lactoglobulin varied with season in direct proportion to the foam stability.  $\beta$ -lactoglobulin concentration had no seasonal trend (8). It was further found that the phospholipid concentration of the milk also varied seasonally, being in inverse proportion to the foam stability (12). These results suggested that foam stability could be increased by adding whey proteins, or decreased by adding phospholipids. Since a relatively unstable foam was desired, work was directed to the addition of a phospholipid, which in our case was soy lecithin.

The simplest procedure for year-round plant op-

eration would be to determine one concentration of lecithin to be added throughout the year. Since the naturally-occurring phospholipids of milk varied seasonally in concentration, one single, year-round concentration of lecithin would be possible only if the naturally-occurring variation in foam stability could be overridden. Earlier research showed that foam stability was related to viscosity (11). This fact was used to solve the dilemma—the natural phenomenon was overridden by increasing the viscosity through an increase in solids content of the concentrate to such a degree that the foam was stable all year round. Then, uniform instability all year round could be accomplished by adding a single ratio of lecithin to milk solids.

#### *Attaining Consistent Quality*

ONCE the foam stability problem had been solved, we directed our attention to improving the drying process so that the best product quality would be consistent with a high output. Thirteen independent variables were identified and seven dependent variables were originally selected to describe proc-

ess efficiency and product quality. The study was carried out over a 3-year period using experimental designs and mathematical model simulation. Prior to the study, it was assumed that if moisture and HMF content were within acceptable limits, the other dependent variables would be also. This proved to be largely correct (6, 7). Although the study was terminated short of completion, a series of 42 runs based on the predictions of the study showed that the process was successful.

As finally developed, this pilot plant (fig. 3) was used to produce a quantity of vacuum foam-dried whole milk—6,600 quart-unit packages—sufficient to support a limited market study in the Lansdale, Pennsylvania area (18). The milk was packaged under nitrogen in cans containing the equivalent of one quart of fluid milk, labelled "Dairy Fresh," and sold from the dairy cases of 9 supermarkets over a 12-week period. The milk was priced 4¢ below the store price of a quart of fluid milk. A cost estimate showed this to be a reasonably profitable figure (21). Even though it was a new item, the product sold well, indicating a good potential for commercial success. Consumer acceptance was high. Purchasers reacted very favorably to the flavor, dispersibility, storage convenience, cost, and richness of the dry milk. A great majority of them considered it as good as or better than fresh whole milk on all factors (18). An interesting finding was that the sales of Dairy Fresh seemed to have no effect on the sales of other dairy products. Apparently Dairy Fresh was purchased for special uses, thus signifying an additional market for milk.

\* \* \*

This research program, which culminated in the successful development of a high quality dry whole milk, exemplifies what can be accomplished when scientists of different disciplines work cooperatively toward a common goal. By the time that research and development activities on the project had drawn to a close, the roster of active participants included chemical and mechanical engineers, chemists, food technologists, micro-biologists, statisticians, and economists. With a few exceptions, the list of authors in the literature cited section represents those who deserve credit for significant contributions to the work.

One point that deserves further emphasis here is that every single phase of the research project was planned and executed with an awareness of the practicality of the whole venture. In other words, our team realized that nothing could be gained unless the methodology was economically feasible. The final economic evaluation, based on calculations for a full-scale operation, showed that this goal was reached. Dairy Fresh *can* be manufactured the year round and sold at a profit. Although no attempt was made to evaluate the potential of the Dairy Fresh market, some indications can be gleaned from the high ratio of favorable consumer reactions in the market study (18). This response is no doubt reflected in the interest currently being noted in the dairy and food processing industries for manufacturing a dry whole milk similar to the Philadelphia product.

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The authors, H.I. Sinnamon and N.C. Aceto, are on the research staff of USDA's Eastern Marketing and Nutrition Research Division, Wyndmoor, Pa.